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CONTRACT TECHNICAL NOTE

THE RADAR ABSORPTION EFFECT CAUSED BY VERY THIN PLASMA SHEATHS

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H.M. MUSAL, JR. AND W.E. BLORE

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A PART OF PROJECT "DEFENDER"

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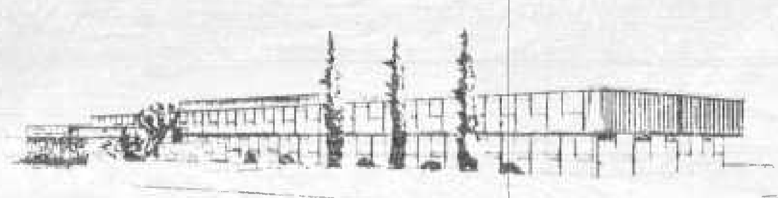

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H.M. MUSAL, JR. AND W.E. BLORE

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THE RADAR ABSORPTION EFFECT CAUSED BY VERY THIN PLASMA SHEATHS

ABSTRACT

The radar absorption effect has been observed in full scale reentry vehicle tests and in laboratory and field studies of hypersonic vehicle flow field observables. The usual manifestation of this effect is the drastic reduction of the radar cross section of the vehicle and its associated flow field under certain conditions. Ballistic range studies of this effect have shown significantly large absorption to occur for even very thin plasma sheaths. This is inexplicable in terms of the theory that explains the full scale vehicle results. A more advanced theory is presented here, which has the potential for explaining the anomalous absorption caused by very thin plasma layers covering blunt metallic bodies. In essence, it is shown that the anomalous absorption may be a diffraction effect caused by the gradient of the electron density in the plasma sheath around the body. That is, the effect occurs when the body is only partially covered by an over-dense plasma sheath. This plasma layer can be very thin compared to the wavelength of the radar wave and still cause a significant decrease in

the radar cross section. These results are illustrated by several theoretical graphs that show the dependence of the radar cross section of a metal sphere partially covered by a plasma layer on the size, thickness and properties of the layer. Finally, this theory is applied to predict the anomalous absorption observed in ballistic range studies. The large amount of absorption observed experimentally is correctly predicted by this theory, but an accurate verification of all the details of the behavior as a function of ambient air density and body speed awaits more extensive and detailed flow field computations.

THE RADAR ABSORPTION EFFECT CAUSED BY VERY THIN PLASMA SHEATHS

INTRODUCTION

The radar absorption effect has been observed in full-scale reentry events, in small-scale field tests, and in laboratory studies. The usual manifestation of the radar absorption effect is the drastic reduction of the radar cross section of the vehicle and its surrounding flow field under certain flight conditions. The decrease in radar cross section is of the order of 10 to 20 db. This effect has been observed in two different flight regimes. It has been observed at high altitudes during reentry of the MIT Trailblazer Vehicle(1). It has also been observed at relatively low altitudes during the reentry of full-scale reentry vehicles(2). The laboratory observations of this phenomenon have been at relatively high ambient air densities and low velocities, which corresponds to the low-altitude observations in the full-scale situation. These observations have been made at GM DRL(3) and at CARDE(4).

Several attempts to explain the radar absorption effect have been made. In the case of the full-scale observations, these have been explained qualitatively and quantitatively by Musal(5). This was done on the basis of a simple geometrical optics approach. Radar wave

destructive interference and real power absorption in the plasma sheath surrounding the nose cone was shown theoretically to give rise to the amount of absorption, and the altitude at which it occurred, actually measured during the reentry. In this situation the thickness of the plasma sheath was of the order of one-half the wavelength of the radar wave. This is approximately the minimum thickness for which the simple geometrical optics explanation will predict large amounts of absorption. In the case of the MIT Trailblazer experiments, Murphy[1] has offered an explanation for the high altitude radar absorption which occurs at relatively high velocities. His explanation is based on the fact that the plasma layer surrounding the vehicle may be much thicker than the shock stand-off distance because of ultraviolet photoionization of the air in front of the shock. This effectively creates a large cloud of low density ionization around the vehicle. There is also gradual radial gradient of the electron density in this cloud. At the radar frequency used in this experiment, a strong interaction between the wave and the ionization cloud was experienced. The net effect was to decrease the backscattering from the entire structure. The ballistic range experimental results obtained at GM DRL and at CARDE are not explainable by either the simple geometrical optics approach or by means of the photoionization assumption. The first explanation is not

applicable because the shock layer is too thin. Calculations have shown that in order to predict the amount of absorption experimentally observed, it would be necessary to assume that the shock layer was three times as thick as was actually measured. The possibility that photoionization would contribute toward a larger ionization cloud around the body was disproved by measurements of the amount of precursor ionization outside of the shock front. This was done in a series of measurements at GM DRL(6).

In order to explain the absorption effect for the thin plasma sheaths that are present in the ballistic range measurements several other mechanisms were investigated. The possibility that the angular gradient of the electron density around the body might cause focusing or defocusing effects was investigated. Using a geometrical optics approach, Musal(7) showed that the refractive effect of the gradient can cause significant focusing and defocusing of the backscattered radar wave. However, it was shown that in order to predict significantly large amounts of absorption by this mechanism, the plasma layer again had to be approximately two or three times as thick as was measured.

The angular gradient in electron density can be considered from another viewpoint. This is the diffractive aspect of such a non-uniform layer. The results of this approach will be outlined here since they appear to contain the basic elements for the explanation of the radar

absorption effect caused by very thin plasma layers on metallic bodies.

THEORY

A theory that appears to offer a possible explanation for large decreases in the radar cross section of a metallic body when it is partially covered by a thin plasma layer is presented here. This theory depends on the diffractive effect of angular gradients in the plasma layer around the body, and predicts large decreases in radar cross section caused by very thin plasma layers.

The radar cross section of a body can be predicted theoretically in exact form if the tangential components of the electric and magnetic fields induced on the surface of the body by the incident radar wave are known exactly (see for example, Mentzer[8]). In the practical situation, the exact fields are usually not known. Thus some approximate method must be used to obtain approximate values of these fields when the body and the incident wave are specified. The well-known physical optics approximation is often used when the body is metallic. In essence, this approximation takes for the tangential induced fields on the surface of the body a magnetic and an electric field which are just equal and opposite, respectively, to the tangential components of the magnetic and electric fields of the incident wave. A suitable integration of these

fields over the illuminated surface of the body then gives the far field scattered wave intensity, from which the radar cross section is determined. In order to extend this theory to the case of plasma covered metallic bodies, it has been assumed that the effect of the plasma layer is merely to change the phase and amplitude of these induced fields. If the layer is very thin this appears to be a reasonably valid approximation. The far field scattered wave is then computed in the same manner as in the usual physical optics approach.

When this technique is applied to the case of a metal sphere covered by a thin plasma layer the resultant integral for the nose-on backscattering radar cross section (σ) can be shown to be

$$\frac{\sigma}{\lambda^2} = \frac{\pi^3 a^2}{4\lambda^2} \left| \int_{x=0}^{x=4a/\lambda} \left(\Gamma_{TM} - \Gamma_{TE}\right)\left(1 - \frac{x\lambda}{4a}\right) e^{+j4\pi\frac{h}{\lambda}}\, e^{-j\pi x\left(1+\frac{h}{a}\right)}\, dx \right|^2$$

where Γ_{TM} and Γ_{TE} are the TM and TE mode reflection coefficients for a metal-backed plasma layer, given by

$$\Gamma_{TM} = \frac{\Gamma_{pTM} + e^{z}}{1 + \Gamma_{pTM}\, e^{z}}$$

$$\Gamma_{TE} = \frac{\Gamma_{pTE} - e^{Z}}{1 - \Gamma_{pTE}\, e^{Z}}$$

where Γ_{pTM} and Γ_{pTE} are given by

$$\Gamma_{pTM} = \frac{\left(1 - \frac{\Omega_p^2}{1 - j\Omega_c}\right)\left(1 - \frac{x\lambda}{4a}\right) - \left[\left(1 - \frac{x\lambda}{4a}\right)^2 - \frac{\Omega_p^2}{1 - j\Omega_c}\right]^{1/2}}{\left(1 - \frac{\Omega_p^2}{1 - j\Omega_c}\right)\left(1 - \frac{x\lambda}{4a}\right) + \left[\left(1 - \frac{x\lambda}{4a}\right)^2 - \frac{\Omega_p^2}{1 - j\Omega_c}\right]^{1/2}}$$

$$\Gamma_{pTE} = \frac{\left(1 - \frac{x\lambda}{4a}\right) - \left[\left(1 - \frac{x\lambda}{4a}\right)^2 - \frac{\Omega_p^2}{1 - j\Omega_c}\right]^{1/2}}{\left(1 - \frac{x\lambda}{4a}\right) + \left[\left(1 - \frac{x\lambda}{4a}\right)^2 - \frac{\Omega_p^2}{1 - j\Omega_c}\right]^{1/2}}$$

and Z is given by

$$Z = -j\,\frac{4\pi h}{\lambda}\left[\left(1 - \frac{x\lambda}{4a}\right)^2 - \frac{\Omega_p^2}{1 - j\Omega_c}\right]^{1/2}$$

and λ is the radar wavelength, a is the radius of the sphere, and h is the thickness of plasma layer. The plasma properties are given by the normalized plasma frequency Ω_p and the normalized electron collision frequency Ω_c, which are

$$\Omega_p = \frac{\omega_p}{\omega} = \frac{1}{\omega}\left(\frac{q^2 N}{\epsilon m}\right)^{1/2}$$

$$\Omega_c = \frac{\nu_c}{\omega}$$

where ω is the radar angular frequency $(2\pi f)$, ν_c is the electron collision frequency, ω_p is the plasma frequency, q is the electric charge carried by an electron and m is its mass, N is the electron number density, and ϵ is the capacitivity of free-space. It can be shown that if the reflection coefficients of the layer are not functions of the angle of incidence, then the above integral can be explicitly evaluated in closed form. This is not the case for a plasma layer. Consequently, the integral must be evaluated by numerical integration.

Some typical results of this approach are shown in Figures 1 and 2. These figures show the radar cross section of a metal sphere as a function of the amount of the sphere covered by a uniform thin layer of plasma. Figure 1 shows the change in the radar cross section as the layer becomes thicker. It can be seen that a layer of only 1/10 of a wavelength in thickness is necessary to give appreciable changes in the radar cross section as the amount of angular coverage is changed. Figure 2 shows the change in the radar cross section as a layer of constant thickness changes in its electron density. A change in electron

density from critical density to 100 times critical density is encompassed.

In order to gain some confidence in the validity of this theory, several experimental measurements have been made involving more controllable configurations and materials. These experimental measurements have shown that the theory is remarkable good, provided that one does not consider bodies which have a large extent of surface nearly parallel to the direction of incidence of the radar wave.

APPLICATION

The diffraction theory will now be applied to the ballistic range experimental situation. A preliminary attempt to predict theoretically the amount of absorption obtained in the GM DRL ballistic range studies of the radar absorption effect is presented here. In order to do this properly, it is necessary to know the spatial variation of the electron density and collision frequency throughout the entire shock layer around the body. The computation of these quantities in the flow field is a very lengthy aerodynamic calculation. The flow field calculation must be repeated at each speed and/or pressure for which the radar cross section is to be calculated. In order to avoid this much extensive work at the present time, we have taken some representative approximate variations

of the flow field properties for use in the preliminary radar cross section calculations. The thickness of the plasma layer was taken to be the thickness of the overdense region of the plasma sheath around the body. The electron density and collision frequency within this overdense region were taken to be the values which existed in the stagnation region for the speed and ambient pressure considered. In order to obtain the dependence of the radar cross section on body speed, the way in which this overdense region thickens and spreads over the body as a function of speed was approximated by extrapolation of limited flow field data[9]. This approach only approximates the actual flow field configuration. Using this approach, the radar cross section was calculated as a function of velocity for the ambient pressure used in the ballistic range studies. The theoretical results are shown in Figure 3, along with the experimental data. It can be seen that a large decrease in the radar cross section, of the order of 15 db, is obtained with the new theory. Previous theories gave approximately 3 db of absorption under these conditions. The details of the fluctuations of the radar cross section at high velocities are probably not significant because the flow field was only approximated and the assumptions that were made were not very good for such a large fractional coverage of the body. As was pointed out earlier, the

theory itself does not appear to be very accurate in this regime either.

The real significance of this theoretical calculation is that a very large decrease in the radar cross section is obtained with only a very thin plasma layer. The details of how the radar cross section varies with speed depend critically on the development of the ionization around the body. Thus there is a need for very good flow field calculations before exact comparisons between the theoretical and experimental results can be made. Work is continuing along the lines of improving the diffraction theory used in the prediction of the radar cross sections of plasma covered metal bodies, and in the calculation of the flow fields around blunt bodies.

CONCLUSIONS

It appears that a theoretical explanation for the large decrease in the radar cross section of a metal body caused by a very thin plasma sheath has been found. The decrease depends on partial coverage of the body by the plasma layer. In other words, it is the angular gradients of the plasma properties around the body that cause severe diffraction of the radar wave. This appears to be the explanation for the anomalous absorption measured in ballistic range studies. This

effect and its theoretical interpretation, when more highly refined, may be useful as a flow field diagnostic technique.

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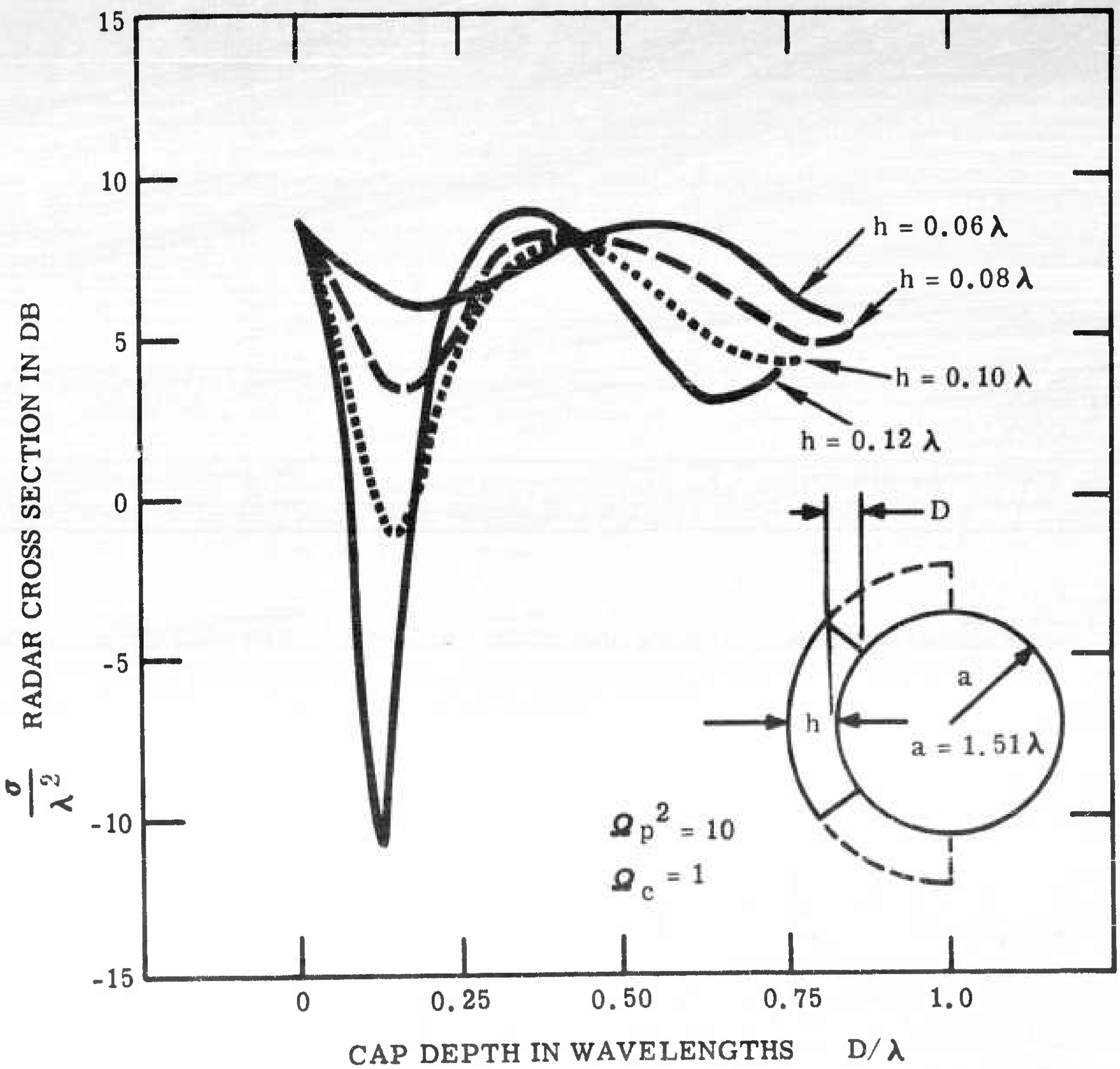

FIGURE 1 Radar Cross Section of Plasma Covered Metal Sphere-Effect of Plasma Thickness

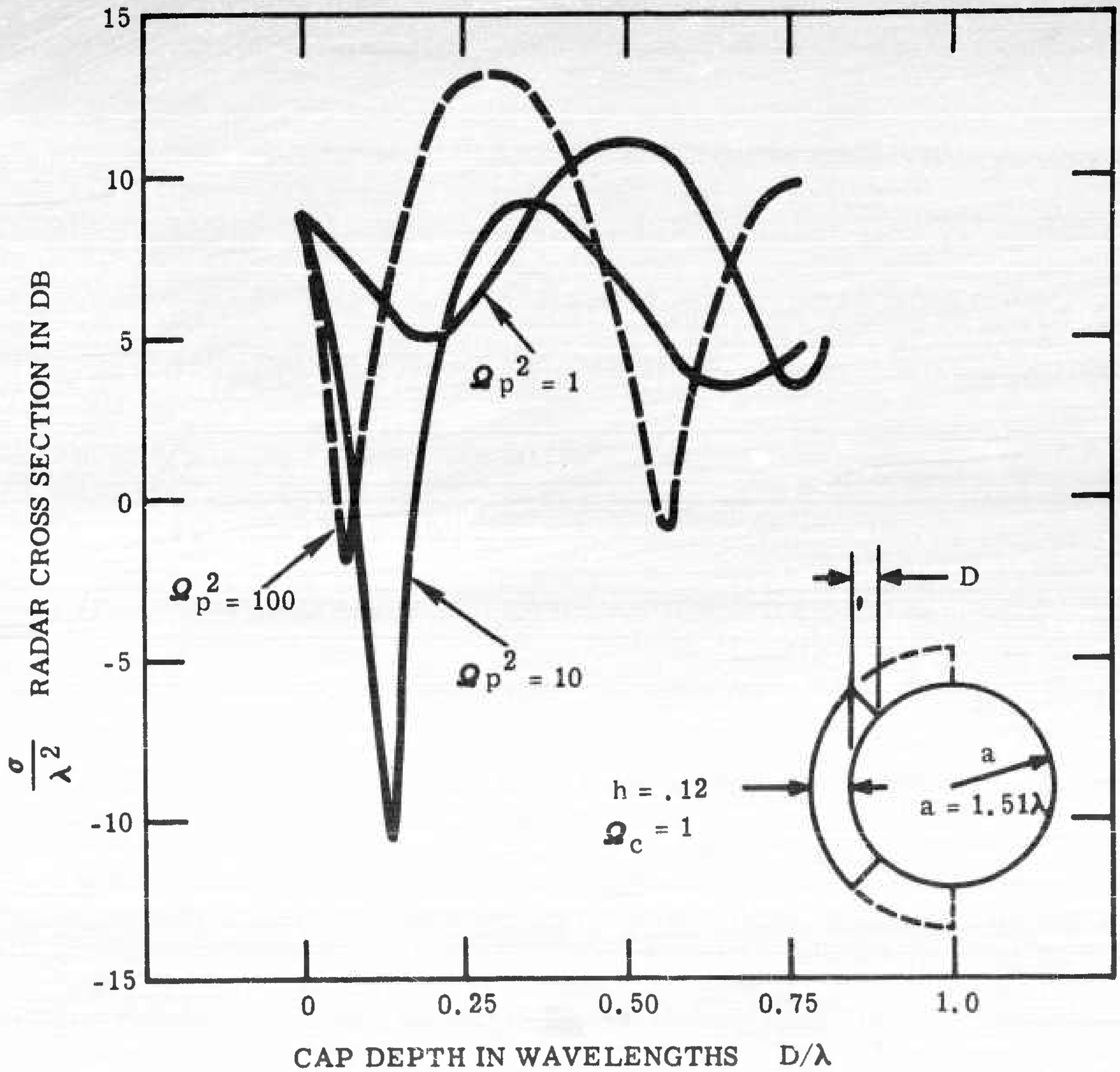

FIGURE 2 Radar Cross Section of Plasma Covered Metal Sphere-Effect of Plasma Density

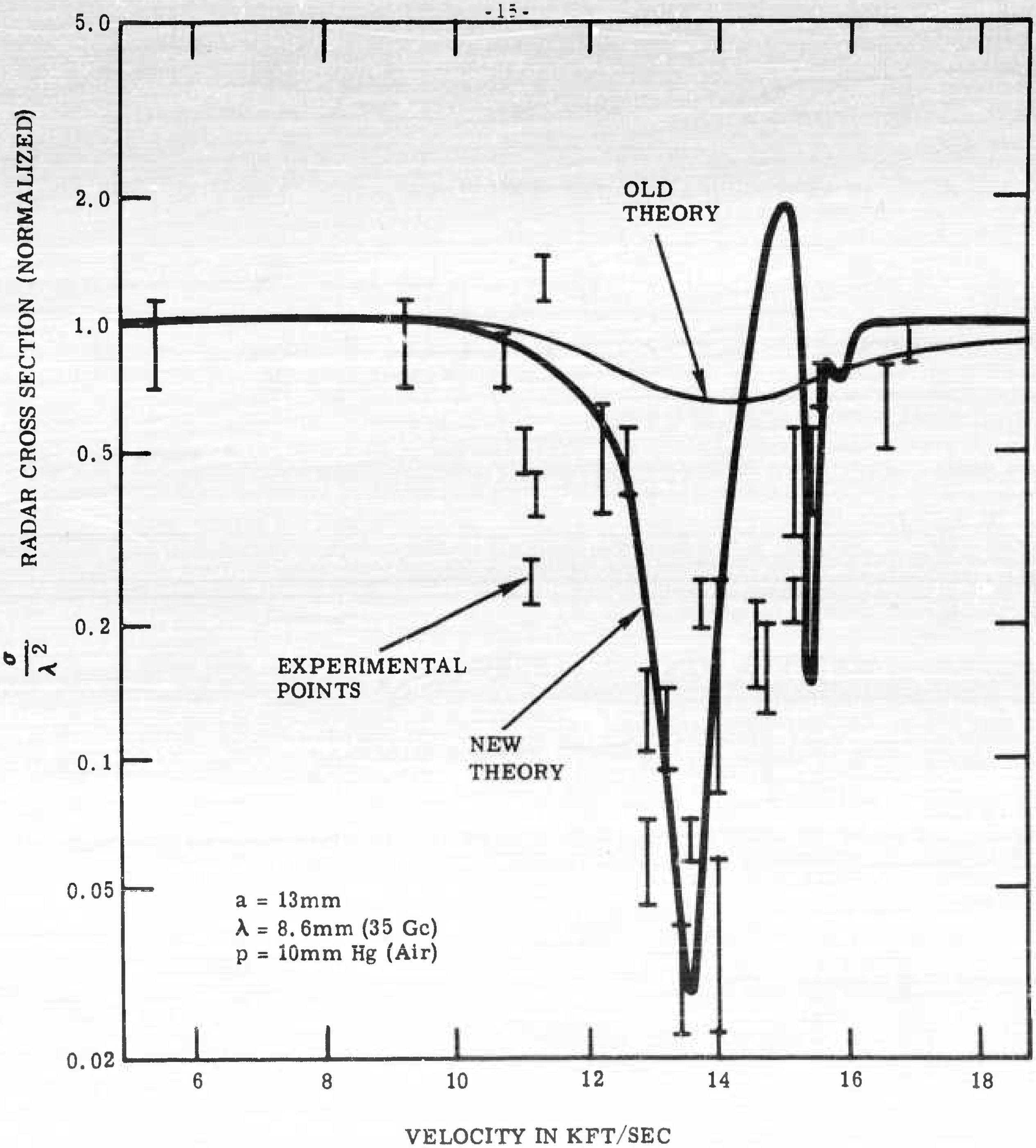

FIGURE 3 Radar Absorption Effect Observed in Ballistic Range Compared to Theory

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